Simulation of Random Jitter in Ring Oscillators with SPICE

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Abstract — A time-domain model of the semiconductor device noise sources that includes operating region dependencies and is suitable for incorporation into the SPICE simulator is presented. Simulation results of the random jitter for practical MOS ring oscillators are discussed.

INTRODUCTION

Noise analysis capabilities are provided in most commercial circuit simulators that have been derived from the original Berkeley SPICE circuit simulator. In most of these simulators, the noise analysis is made in the frequency domain. Some applications exist, however, where the small signal frequency domain analysis will not provide the performance needed to accurately predict the effect of device noise on circuit performance. Included in these applications are high-speed Voltage Controlled Oscillators and Phase Locked Circuits where the time jitter plays a key role in circuit performance. A time-domain transient analysis is useful for predicting the jitter performance of these circuits. Unfortunately, neither a time-domain noise source nor a random number generator is available for transient simulations in most of these simulators. Since the source code for the commercial SPICE tools is not generally available for adding a time-domain noise analysis capability, an external transient noise input can provide widespread access to SPICE users.

Bolcato and Poujois [1] presented a transient noise simulation that was incorporated into the circuit simulator ELDO. More recently Weigandt et el. [2] and Mc Neill [3] have referenced transient noise simulations using SPICE but they have not provided details about the simulation methods. The approach we will follow here is based upon applying time-domain device noise through the Piecewise Linear Source elements that are available in most SPICE simulators. This seemingly straightforward approach is similar to that discussed by Hageman [4] but is complicated by the observation that in circuits such as ring oscillators, the individual MOS transistors have noise current spectral densities that change substantially during each period of oscillation as the transistor goes between the cutoff, triode and saturation regions. In addition, at high frequencies the device drain current can not be used to determine operating regions since substantial drain current may be flowing through parasitic capacitors even after the transistor enters the cutoff region.

TIME-DOMAIN NOISE REPRESENTATION

Device noise in MOS transistors, bipolar transistors and resistors is modeled with time-domain current sources that are internal to the device models and that are characterized by well-known spectral densities. Since frequency domain noise analysis does not depend upon details about the time-domain waveforms, the time domain noise waveforms are not readily available. Our approach will be to generate a time-domain noise source for each noise source internal to the electronic devices that comprise a Ring Oscillator circuit. The piecewise linear (PWL) current source element that is available in most SPICE simulators will then be used as an input of these noise sources into the simulator.

Programming languages such as C++ or tools such at MATLAB can be used to generate a discrete-time noise source that is spectrally flat denoted by the sequence $<W(nT)>$ in Fig.1. This can be readily attained with a random number generator available in these tools. In our simulations, we used a generator that was uniformly distributed between -1 and +1. If the amplitude spectrum is not acceptable, the individual samples can be amplitude shaped. For example,

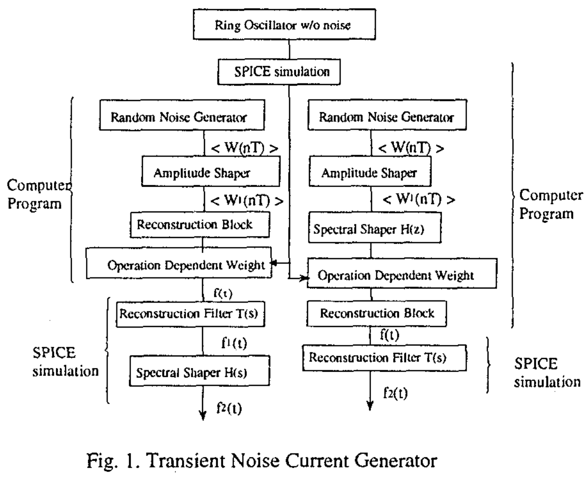

Fig. 1. Transient Noise Current Generator

some noise sources have Gaussian amplitude distributions. To obtain a Gaussian amplitude, the amplitude would be shaped with the equation

$$w_1(nT) = [sign(w(nT)]\sigma\sqrt{2}erf^{-1}\left(\frac{|w(nT)|}{2\sqrt{2}\sigma}\right) \qquad (1)$$

where $\{\sigma\}$ is the standard deviation of the Gaussian amplitude distribution. This amplitude shaping does not affect the spectral response and thus <W1(nT)> in Fig.1 remains white. The signal <W1(nT)> needs to be spectrally shaped and reconstructed. Spectral shaping is required when modeling non-white noise sources. Reconstruction is needed to convert the discrete time sequence into a continuous-time function. A zero-order sample and hold with practical rise and fall times at the transitions is commonly used for the reconstruction block. If the noise bandwidth is wide, the reconstruction filter is needed to correct for the frequency distortion caused by the zero-order sample and hold. The zero-order sample and hold has a z-domain transfer function magnitude of

$$|H(z)| = \frac{2\sin(wT/2)}{w} \qquad (2)$$

where T is the period of the sample and hold. The reconstruction filter should realize the inverse of this transfer function.

The method on the right in Fig.1 uses discrete-time domain spectral shaping with H(z). The left does the same shaping in the continuous-time domain with H(s). In the former, a high-level computer program is used to implement the digital filter. In the later, a component-level filter synthesis of H(s) is required but the actual filtering is done with the simulation of the circuit via SPICE. In either case, the time-domain function $f_2(t)$ serves as the continuous-time noise source that will be used to model the noise in a single device.

A three-stage CMOS ring oscillator is shown in Fig. 2. Fig. 3 shows the time-domain waveform for the voltage Vo(t) if the ring oscillator is implemented in a 2u CMOS process

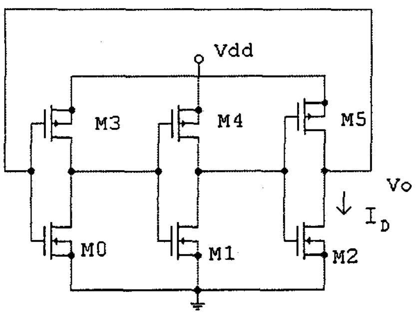

Fig.2 3-stage CMOS Ring Oscillator

available through MOSIS. In this simulation, the transistors were assumed noiseless. The device sizes used in simulating this oscillator were Wn=3u, Ln=2u, Wp=8u and Lp=2u. On the same time axis, the corresponding current for M2 and the region of operation for both M2 and M5 are shown. From this plot, it can be

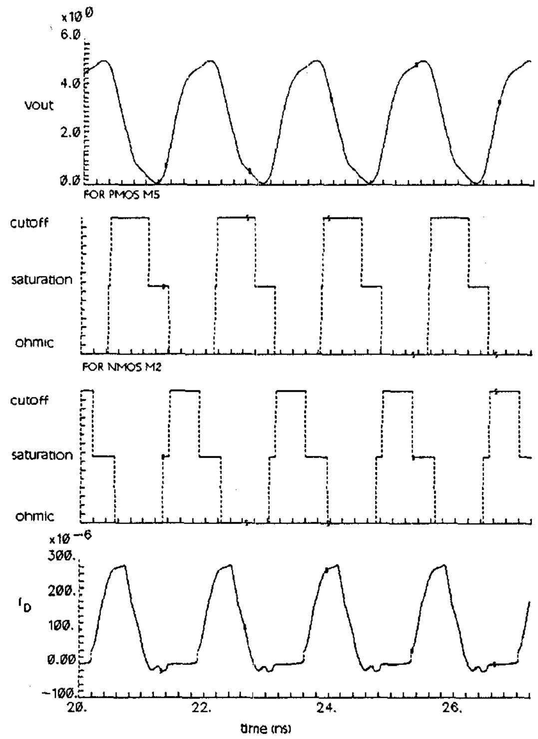

Fig. 3 Region of Operation of M2 and M5

observed that M2 and M5 makes transitions between cutoff, ohmic and saturation during each period.

A model of the MOS transistor including the thermal channel noise is shown in Fig. 4 where the current source In is a white noise source. It is well known that the current spectral density of this thermal noise source is both operating region and current level dependent. The spectral density of this thermal noise is often modeled by the equations

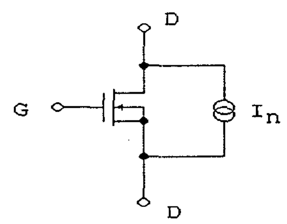

Fig. 4. Noise Model of MOS Transistor

$$S_I = \begin{cases} 0 & cutoff \\ \dfrac{4kT}{R_{FET}} & ohmic \\ \dfrac{8kTg_m}{3} & saturation \end{cases} \qquad (3)$$

where

$$R_{FET} = \frac{L}{uC_{ox}(V_{GS} - V_T - V_{DS})W}$$

$$g_m = \frac{uC_{ox}(V_{GS} - V_T)W}{L}$$

RFET is the drain to source ohmic impedance and gm is the transconductance of the device. Corrections for the discontinuities in spectral densities are not included in the model of (3) and we will not focus on these corrections in this paper. Although gm is drain current dependent, the transient time domain drain current of the MOSFET is not readily attainable since simulations will include in the simulated drain current the current flowing through any parasitic capacitance connected to the drain. The parameters RFET and gm can be expressed in terms of the port voltages and when expressed this way, the port voltages do determine the operation region dependent spectral density.

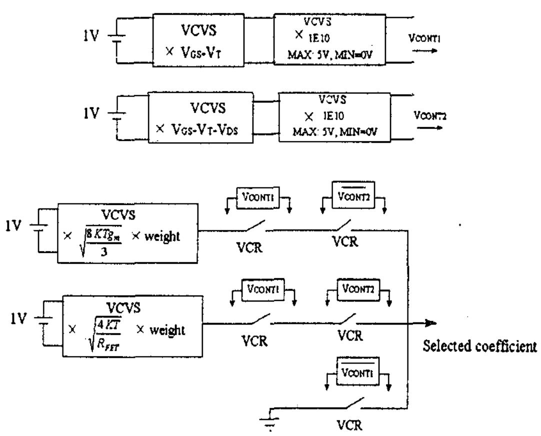

Fig.5 Operation Region Detection Circuit

Because of the operating point dependence of the spectral density, a time-dependent weighting factor is needed to weight the time-domain white noise source. This is represented by the Operation Dependent Weight block shown in Fig. 1. A simple circuit that can be used to determine the region of operation of a MOS transistor is shown in Fig. 5.

This circuit is included in the original noiseless SPICE simulation and the outputs from this simulation serves as an input file to the computer program that generates the piecewise linear time-domain noise sources.

SIMULATION ENVIRONMENT

After the operation-dependent noise for each device is obtained, the circuit is re-simulated with the inclusion of the piecewise linear noise current sources. The presence of noise not only contributes to jitter in the network but also contributes phase-slip between the regions of operation predicted from the ideal simulation and those obtained when the noise sources are included and this phase-slip will increase with time. If the phase-slip becomes substantial, the operation region dependent information from the initial noisy simulation can again be passed to the Operation Dependent Weight block and new piecewise linear noise sources can be generated with the computer program. These then become the noise inputs for a second noisy simulation. If a second noisy simulation is required, it is important to use the same seed in the random noise generator that was used for the first noisy simulation.

In our simulations, minimal phase-slip was experienced during the first noise analysis for simulations that were 75nsec long so no phase-slip adjustment was required. If phase-slip is observed on longer simulation runs, additional updating of the operation region dependence of the noise current sources may be required.

To maintain phase alignment between the ideal and noisy simulations, it is important that both oscillators start at the same time. Allowing roundoff errors in the simulator to start the oscillation generally results in considerable phase slip between the noisy and noiseless oscillator. A short-

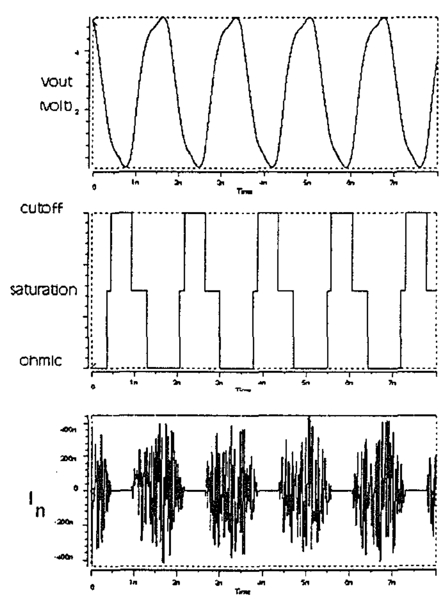

Fig. 6. Simulation Waveforms with Noise

duration pulse applied at the start of the simulation has proven effective at starting the oscillators together.

An alternative approach circumvents the need for the compensation for the phase-slip between the ideal and noisy oscillators by embedding the circuit of Fig. 5 into the ring oscillator itself. In this approach, the Operation Dependent Weight is embedded in the SPICE simulator and this circuit automatically selects the correct region of operation and provides the correct weight of the white noise current as governed by (3) during the transient simulation. The latter approach, however, requires considerably more simulation time which becomes an issue when long or multiple transient runs are made with different seeds to the random number generator.

SIMULATION RESULT

The ring oscillator of Fig. 2 was simulated at room temperature. Only thermal noise effects were included in this simulation. The nominal oscillation frequency with no noise was 585.995 MHz. With noise, the nominal oscillation frequency changed 0.005%. The time-step, T, in the discrete-time noise generator was set at 10psec thus band-limiting the white noise to 50GHz. A zero-order sample and hold was used for the reconstruction block. Since the oscillation frequency was considerably below the noise bandwidth, a reconstruction filter for compensating the frequency response of the zero order sample and hold was not included. The PWL current source was updated every 10psec as well. A maximum step size of 0.5psec was used in the transient simulation. A selected time-domain noise current waveform for M2 obtained by the operation region dependent weighting is shown in Fig. 6 along with the output voltage Vo. The strong dependence of the noise on operating region of the device is apparent.

The phase jitter was defined to be the standard deviation of the sequence T1, T2,... TN where N was the number of

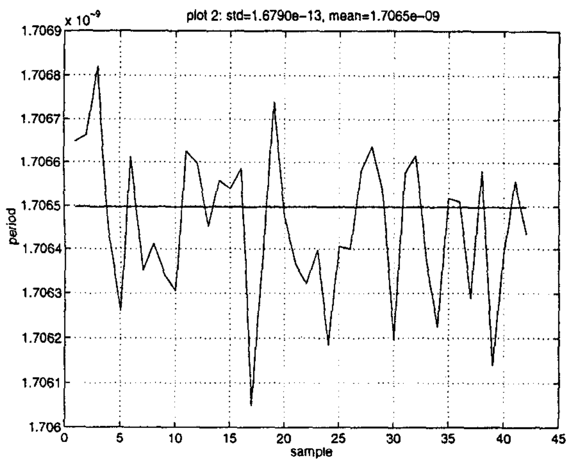

Fig. 7. Random Jitter from Transient Simulation

periods in the simulation interval and where Ti is the length of the ith period. The output periods for one typical simulation run are shown graphically in Fig. 7. Simulation results for 5 different seeds for the noise source provided simulation RMS jitter of 172, 168, 149, 153 and 160fsec. respectively from 75nsec simulations.

These results can be compared with those given in [2]. The ring oscillator of Fig. 2 has less stages and hence a somewhat different operation region spectral dependence than was assumed in the simulations of this reference. Also, the number of noise sources per stage contributing to jitter in the simple oscillator of Fig. 2 are less than those for the oscillator in [2]. In [2], the RMS timing jitter per delay stage was in the 150fs to 200fs range for devices comparable in size to those used in the simulations presented in this paper. It can be observed that the simulated phase jitter per stage in the oscillator of Fig. 2 were somewhat less than those reported in this reference.

CONCLUSIONS

A simulation environment suitable for predicting the time-dependent phase jitter in CMOS ring oscillators has been presented. This environment used a conventional SPICE simulator in the transient simulation mode. Time-domain noise sources for all MOS transistors were externally applied using the piecewise linear current sources. Although this simulation environment focuses on CMOS ring oscillators, the approach is readily extendable to other applications that require a time-domain noise analysis.

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